
dr. Sanneke van Asselen
Researcher at Deltares


Gilles Erkens
Researcher at Deltares and the Department of Physical Geography, Utrecht University

MONITORING SHALLOW SUBSIDENCE IN CULTIVATED PEATLANDS

Introduction

This paper relates to, and partly overlaps with, the paper of Van Asselen et al. (2020).

A large part of the coastal plain of the Netherlands contains as much as several meters of peat in the subsurface (Erkens et al., 2016). Like many other coastal plains worldwide, the Dutch coastal plain is subject to shallow land subsidence from both anthropogenic and natural causes (Erkens et al., 2016; Van Asselen et al., 2018; and references therein). Subsidence increases flood risk, causes damage to buildings and infrastructure and an overall increase in soil wetness as the surface approaches the phreatic groundwater level. In agricultural areas this translates into a lower soil-bearing capacity. In the Dutch coastal plain, subsidence has especially been caused by peat oxidation, peat compaction and peat mining in the Holocene sequence, starting about 1000 years ago (Erkens et al., 2016). Large-scale peat mining continued until the late 19th century, after which subsidence has been mainly caused by peat compaction and oxidation. Peat compaction is the mechanical process of densification of the soil, caused by loading and/or a decrease of the pore water pressure. Peat oxidation refers to the bio-geochemical degradation of organic material by micro-organisms and occurs especially when peat is exposed to oxygen, for example following groundwater level lowering. Peat oxidation also causes emission of greenhouse gasses.

The amount and rate of shallow subsidence in organic-rich coastal sequences is determined by (1) geotechnical and biogeochemical properties of organic and mineral facies, (2) structural loading and (3) groundwater level fluctuations. These three aspects generally vary considerably in both time and space. Consequently, the amount and rate of subsidence is spatially and temporally variable: it varies between polders and even within parcels. During recent years, there is a growing incentive to reduce both subsidence and greenhouse gas emissions in cultivated peatlands. To develop effective measures to reduce subsidence, and to be able to monitor results of implemented measures, a subsidence monitoring system is needed that captures the temporal and spatial variability of land subsidence, and preferably also discriminates between the contribution of different subsidence processes. Examples of mitigation measures are permanently raising the groundwater level or implementing submerged drainage (Pleijter and van den Akker, 2007). The desired monitoring system should be able to measure subsidence at mm-scale accuracy, since long-term net average land subsidence rates are typically on the order of mm to cm yr^{-1}. Also, the system should not severely impact farming activities.

To design and optimize such a system, four different methods are applied to monitor land subsidence of meadows at eight livestock farms in a cultivated peatland area in the north-eastern part of the Netherlands (figure 1). The subsurface of the study area generally consists of a Holocene peat layer (Nieuwkoop Formation; De Mulder et al., 2003) as much as about 3.5 m thick, on top of a thick (tens of meters) Pleistocene sand deposit (mainly Boxtel and Kreftenheye Formations; De Mulder et al., 2003). In the western part of the study area, the peat layer is covered by a few dm-thick clayey top layer (figure 1; Naaldwijk Formation; De Mulder et al., 2003).

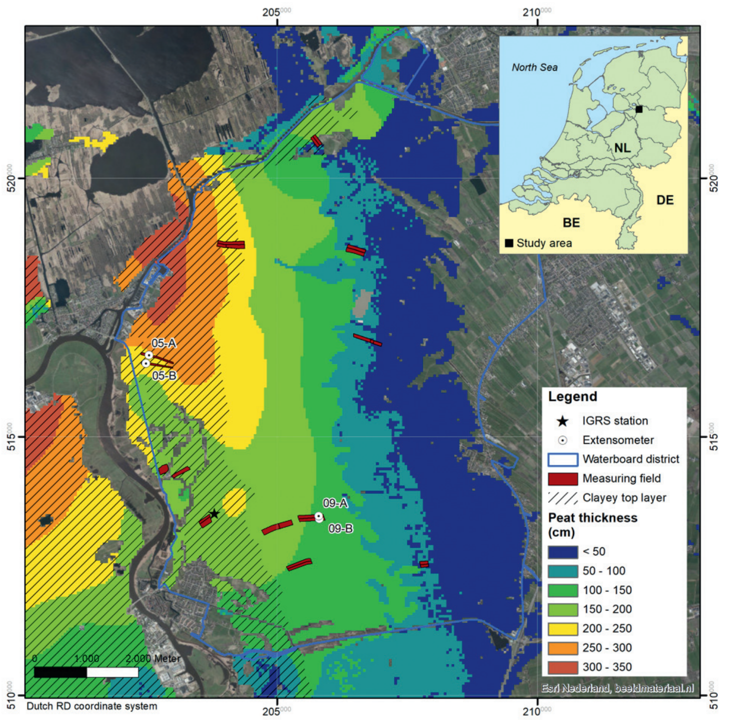

Figure 1 – Peat thickness map for the study area in north-eastern Netherlands (source: Waterboard Drents Overijsselse Delta). Locations of the measuring fields (meadows) at the eight livestock farms, the extensometers and the IGRS station are indicated.

The methods used include conventional (spirit) levelling, extensometery, LiDAR (Light Detection And Ranging) and InSAR (Interferometric Synthetic Aperture Radar). Levelling is a well-tested and often-used technique for measuring surface elevation and has also been applied in a few cases in peat areas in the Netherlands (Pleijter & van den Akker, 2007). Extensometery is applied worldwide for measuring vertical movement of (sub)surface levels but have rarely been applied in peat areas. Both of these field-based techniques result in accurate (mm-scale) point measurements. The use of LiDAR and InSAR for measuring land subsidence in peat areas is promising but still experimental and the accuracy of the measurements needs testing. These two remote sensing techniques may ultimately result in timeseries of maps with spatial coverage, which is needed to monitor the temporal and spatial variability of land subsidence and the effects of applied mitigation measures. In this paper, the four methods are described, and preliminary levelling, extensometery and LiDAR

SUMMARY

To develop a land subsidence monitoring system for cultivated peatlands four measuring techniques are applied in the north-eastern part of the Netherlands, including spirit levelling, extensometery, LiDAR and InSAR. The desired monitoring system should be able to capture long-term spatial and temporal subsidence trends at mm-scale accuracy. Preliminary levelling and extensometery results demonstrate seasonal and shorter-term dynamics with a total vertical movement of up to 35-40 mm in one-year time. A longer (multiple years) monitoring and experimenting period is needed to be able to determine long-term net subsidence (or uplift), and to optimize the subsidence monitoring system for peatlands.

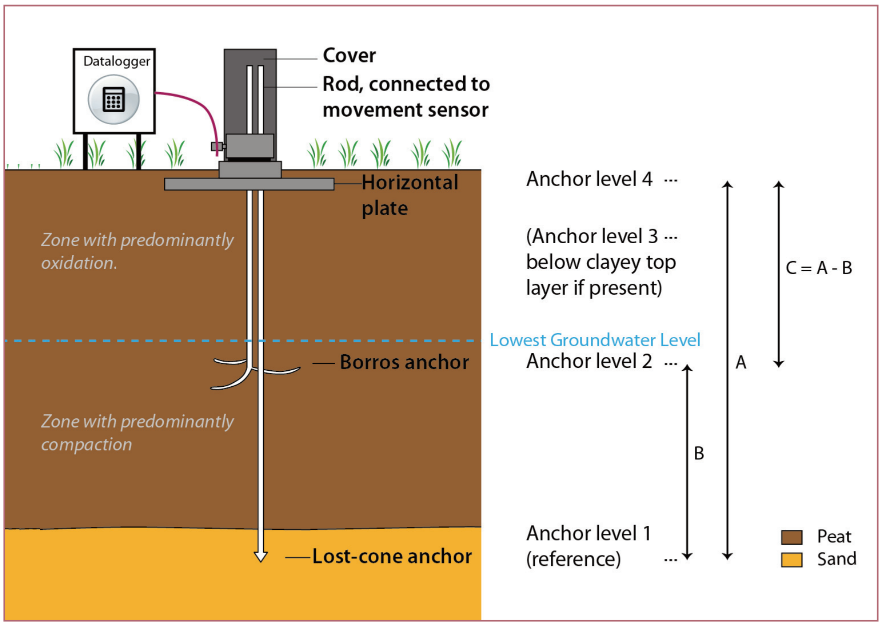

Figure 2 – Schematic representation of the extensometer set-up.

Figure 3 – Integrated Geodetic Reference Station nearby Rouveen (Photo by H. van der Marel).

results and conclusions are presented. InSAR results are not available yet.

Methodology

SPIRIT LEVELLING

The levelling methodology is based on Pleijter and van den Akker (2007). Surface elevations of parts of meadows are measured relative to a reference point, consisting of an iron rod that is founded in the semi-stable Pleistocene sand underlying the Holocene peat layer. Elevations are measured four times a year, using a Leica LS15 levelling instrument and rod, along four section lines of 50 m long and lying 8 meters apart, at a 2 m interval as determined with a measuring tape, resulting in 104 point measurements. The start and end of the section lines are fixed coordinates determined each measuring campaign using a Topcon GRS-1 RTK-GNSS. At local scale, the surface elevation is also measured at ten points closely distributed around the reference point. In each meadow where surface elevations are measured, also the phreatic groundwater level and ditch water level are monitored using standpipe piezometers.

The spatial variability of surface elevations in peat meadows is usually higher than the long-term vertical movement of the surface due to peat compaction and oxidation. Surface irregularities are, for example, caused by cow tracks or grass tussocks. Therefore, a horizontal plate of 10 x 10 cm is fixed to the bottom of the levelling rod to average out the smallest irregularities of the grass-covered surface. For each measuring campaign, the average elevation and the average elevation difference relative to the first measurement campaign in November 2018 (T0) are calculated per measuring field (n =114).

EXTENSOMETER

Extensometers are used to measure deformation worldwide (e.g., Poland, 1984; Sneed and Brandt, 2015). However, they have rarely been applied in peat soils. Extensometers can be used to derive point measurements of vertical movement of different (sub)surface levels at mm-scale accuracy, and to determine the contribution of different subsurface layers, and in some cases processes, to total subsidence. In this study, we installed four extensometers that continuously measure the vertical movement of (sub)surface levels (for locations see figure 1). Different types of anchors are used at three or four different (sub)surface levels (figure 2). Anchor level 1 is a lost-cone anchor founded in the Pleistocene sand. This level is stable at the timescales considered (years), and hence, is used as reference level. Anchor level 2 is a Borros anchor positioned just below the average lowest groundwater level. At this level, vertical movement is measured that is mainly caused by processes acting in the saturated peat layer between level 1 and 2 (B in figure 2), presumably mainly compaction. In the overlying unsaturated zone, peat oxidation is likely to be the dominant process causing long-term subsidence. Anchor level 3 is a small rod pushed into the subsurface just below a clayey top layer, if present (not visualized in figure 2). This level measures the contribution of the entire peat layer (total subsidence A in figure 2 minus contribution of clay layer, if present). Anchor level 4 is a perforated square stainless-steel plate of 0.4 x 0.4 meter positioned at about 5 cm below surface. This level measures vertical movements of the surface relative to level 1 (A in figure 2).
All sensors at the different levels are connected to a datalogger installed at the surface (figure 2). The vertical movement of the different levels is continuously and automatically measured at 1-hour intervals.

LIDAR

LiDAR (Light Detection And Ranging) is a technique that uses laser pulses sent from a laser scanner. The distance from the scanner to the surface or an object on the ground surface is determined by measuring the time gap between emitting the pulse and receiving the reflected pulse. LiDAR surveys result in spatial maps of surface elevation. Timeseries of these maps can be used to analyse vertical movement of the surface. In this study, LiDAR is used to measure surface elevation once every three months at the eight farms. To compare different measuring platforms, the laser scanner is attached to a small aircraft and a drone. The absolute accuracy of such LiDAR measurements in a rural area is 0-3 cm. To increase this accuracy, which is required to monitor land subsidence, Ground Control Points (GCP) are constructed in each parcel. A GCP consists of a 50 cm long hollow aluminium rod with a 50 x 50 cm horizontal plate on top of it, that can easily be placed on the founded reference rods used for levelling. All LiDAR measurements in a parcel use the centre of the horizontal plate as reference. Because this centre has a known height as established by GPS measurements, the accuracy of the LIDAR measurements increases to mm-scale.

An AL3-32 Phoenix laser scanner is attached to a DJI M600pro drone. The drone is manually lifted into the air, after which it automatically follows a pre-defined path using barometric and GPS for orientation. All measurements are real-time visualized on a ground station (laptop), using Wi-Fi or 3G, allowing for real-time quality control during the measurements. RTK-GNSS and Motion Sensor data are post-processed to attain the highest possible accuracy of the position of the drone. These data are linked to the LiDAR data and translated into a point cloud dataset, which is used to create a Digital Elevation Model (DEM). Outliers, vegetation and other objects are filtered out of the dataset. Point cloud classification is done using the international standard as utilized by the American Society for Photogrammetry and Remote Sensing (ASPRS). The final processed point cloud dataset is related to the centre of the GCP as explained above.

The same method is used for the LiDAR measurements with aircraft. For these measurements, a Riegl VUX1LR laser scanner is fixed to a Tecnam P2010 aircraft, using an Inertial Measurement Unit (IMU) for an accurate determination of the X,Y,Z position. The aircraft flies at 305 m elevation above the ground surface at 130 km h-1. The data point density is on average 10 points per square meter.

INSAR

InSAR (Interferometric Synthetic Aperture Radar) uses satellite radar images of the earth surface. Each year, tens of images are obtained of the same area. Based on phase differences of reflected radar waves, changes in elevation are derived from the radar image time series. The radar signal is reflected by (objects at) the surface. InSAR measurements result in a spatial gridded map of reflections of the surface, which can be translated into a map of change in elevation. Most accurate measurements of elevation (phase) change are derived for permanent objects that consistently reflect the radar signal. Good reflection objects are for example rooftops and roads. Vertical movement of such objects can usually be determined with (sub)mm-scale accuracy. In rural areas there are generally a lower number of consistent reflectors, and hence, the use of InSAR is more challenging in terms of attaining a similar accuracy. Increasing the accuracy in rural areas can be done by relating radar data to accurate ground measurements of elevation change by other field techniques and by sophisticated algorithmic data processing by for example better defining temporal correlations.

For the use of InSAR for measurements of land subsidence in the study area an Integrated Geodetic Reference Station (IGRS) has been constructed and

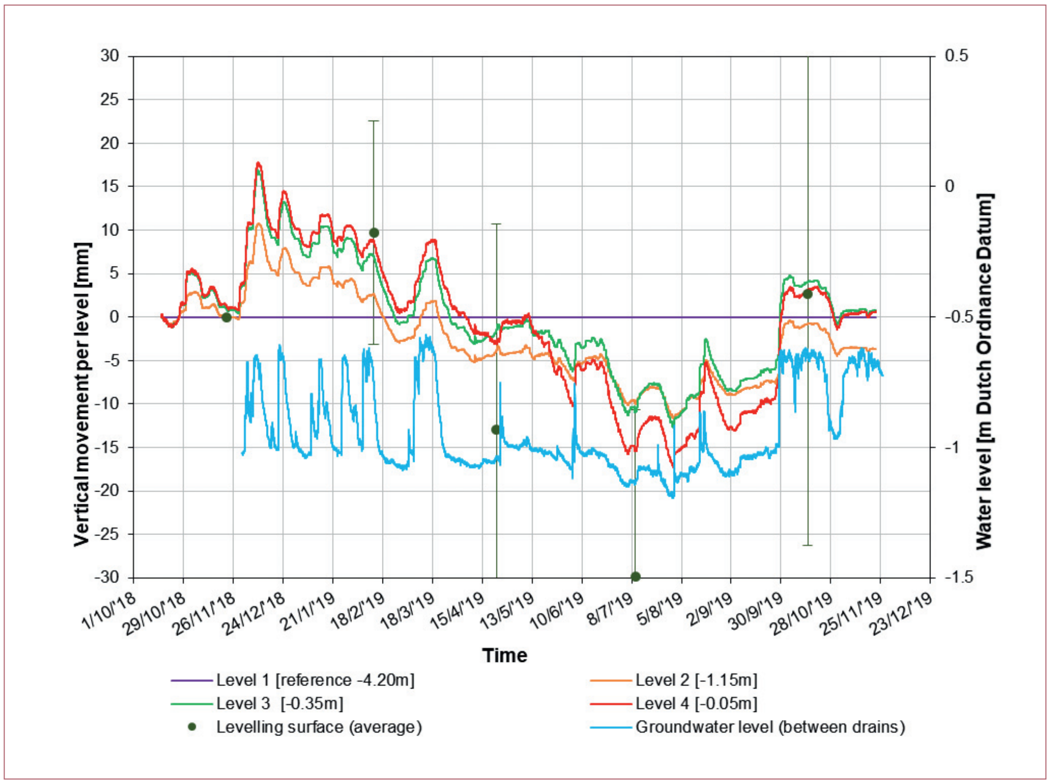

Figure 4 – Preliminary results of extensometer, levelling and groundwater level measurements (site 05-B; figure 1). Green dots represent average elevation difference relative to T0 (November 2018), with standard deviations indicated by vertical bars. Peat thickness at this site is about 3.3 m.

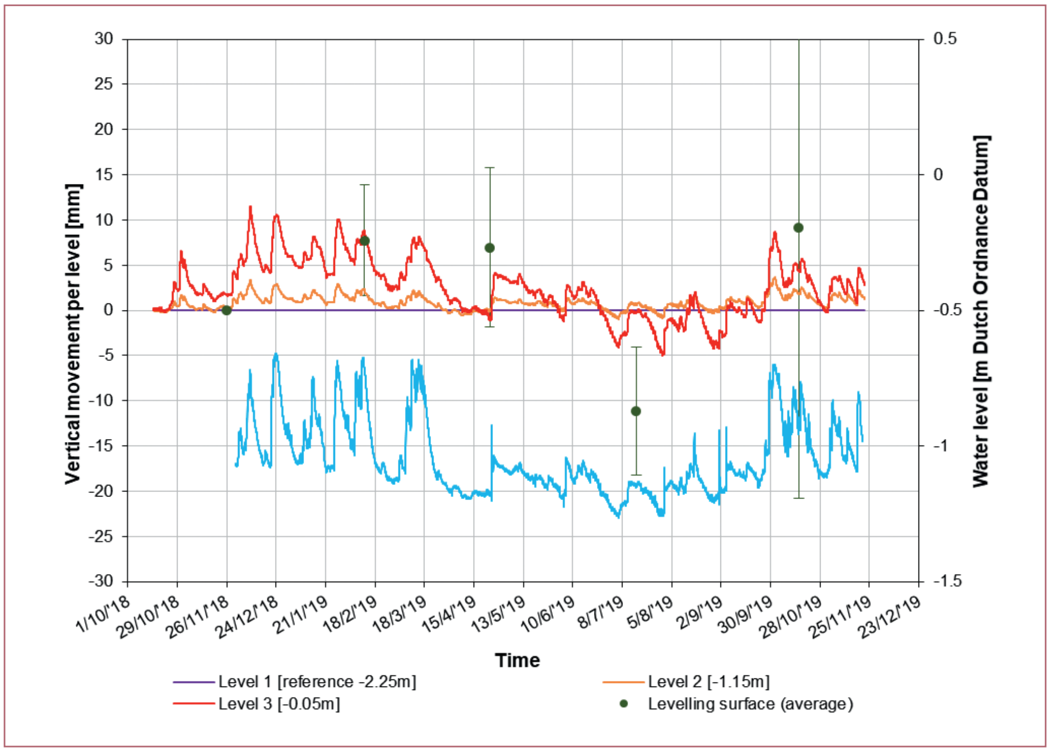

Figure 5 – Preliminary results of extensometer, levelling and groundwater level measurements (site 09-B; Figure 1). Green dots represent average elevation difference relative to T0 (November 2018), with standard deviations indicated by vertical bars. Peat thickness at this site is about 1.5 m.

installed by Delft University of Technology (figure 3; for location see figure 1). The IGRS basically consists of a GNSS antenna on a rod that is founded in the Pleistocene sand, with radar reflectors and a horizontal plate attached to it. Changes in elevation in the surrounding area, as determined from InSAR data, use the IGRS station as reference level. In addition, the vertical movement of the Pleistocene subsurface, assumed to be stable, can be determined. If the Pleistocene subsurface is not stable, these measurements can be used to correct other land subsidence determinations.

Preliminary results

LEVELLING

The results of four measuring fields (two at site 05 and two at site 09; figure 1) are presented in Table 1. Relative to the first measurement in November 2018 (T0), all fields have on average risen about 8 to 10 mm in February 2019. Thereafter, compared to February 2019, all fields show a subsiding trend during spring and summer. The greatest total vertical movement measured in the period November 2018 to October 2019 is about 40 mm (+10 to -30 mm), measured at 05-B (Table 1).

Table 1 - Average vertical movement relative to T0 (November 2018; n=114). *Standard deviation in italic.* Total vertical movement for a specific field = max rise – max subsidence. All in mm.

Field	Feb 2019	Apr 2019	Jul 2019	Oct 2019	Total vertical movement
05-A	8.2 *(12.5)*	-20.1 *(13.4)*	-25.9 *(11.8)*	27.8 *(32.7)*	34.1
05-B	9.7 *(12.9)*	-13.0 *(23.7)*	-29.9 *(19.2)*	2.7 *(29.0)*	39.6
09-A	9.4 *(8.0)*	4.4 *(10.8)*	-10.4 *(9.8)*	10.1 *(33.4)*	19.8
09-B	7.8 *(6.1)*	7.0 *(8.8)*	-9.4 *(7.1)*	9.2 *(29.9)*	17.2

EXTENSOMETER

Extensometer results for locations 05-B and 09-B are presented in figures 4 and 5 respectively. These figures also include the averaged levelling values (of elevation differences relative to T0) with standard deviations for these fields. Results of both methods demonstrate a seasonal dynamic with a general rise in autumn/winter and a subsiding trend in spring/summer. Extensometer results demonstrate that shorter-term fluctuations strongly relate to groundwater level fluctuations. At location 05-B, the total vertical movement relative to October 2018 (T0) has been 35 mm (+18 to -17 mm). At location 09-B, the total vertical movement has been 17 mm (+12 to -5 mm). We observe that processes acting in the saturated peat layer significantly contribute to total surface movements (orange line in figures 4 and 5).

LIDAR

The amount of vertical surface movement, derived from the elevation difference between the LiDAR maps of April and July 2019, shows a general subsiding trend in this time period (figure 6). The dominating greenish colour indicates a general surface lowering of 0 to 50 cm. However, the eastern (right) part of the northern field generally shows a higher amount of subsidence, while the middle part of the northern field shows a surface rise. This is attributed to mowing activities: the eastern part was mowed shortly before the LiDAR measurements while the middle part was not yet mowed. These observations demonstrate the influence of grass height on LiDAR measurements. Also, striping effects are seen in the resulting elevation maps (figure 6).

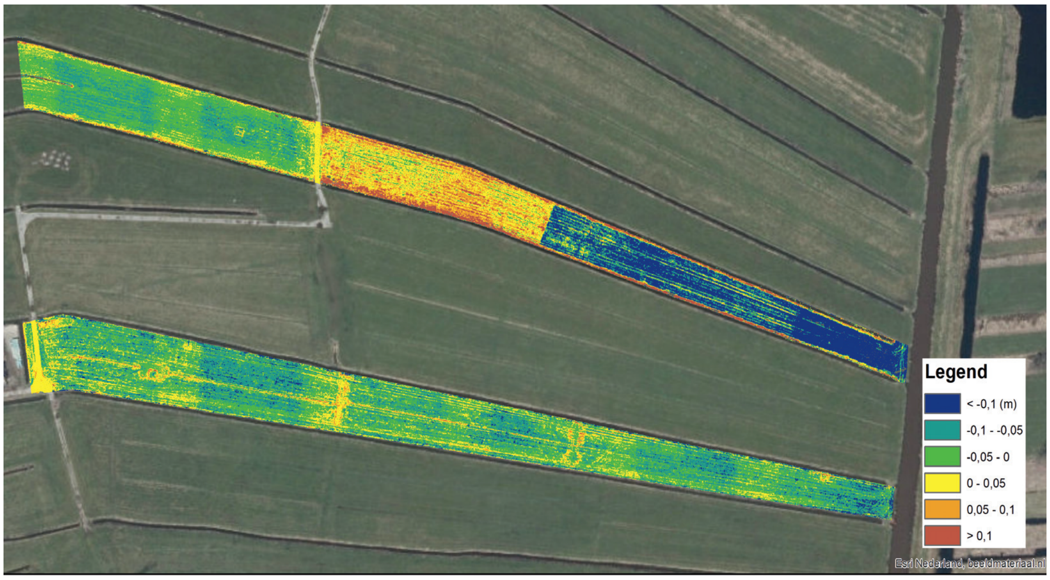

Figure 6 – Land subsidence at site 05 (see Figure 1) derived from the difference between LiDAR elevation measurements of April and July 2019.

Experiences and preliminary conclusions

A unique land subsidence monitoring site in a cultivated peat area in the Netherlands is presented. Our first experiences with applying the different methods are:

- Levelling at farm scale is time-consuming, and therefore, will not be effective at regional scales.
- Extensometer results very convincingly show seasonal and short-term (groundwater-related) vertical movements of different sublayers, i.e. processes.
- LiDAR results in spatial map but results demonstrate the influence of grass height. This method needs optimization aiming to reduce effects of grass height and increase the accuracy of land subsidence determinations. Moreover, the method is very much weather-dependent (it should not be too windy) and thus more difficult to plan. Also, the use of a drone and/or aircraft may disturb cattle due to noise pollution.
- InSAR results are not available yet.

Preliminary levelling and extensometry results demonstrate seasonal and shorter-term dynamics with a total vertical movement of up to 35-40 mm in one-year time. This proves that a long (multiple years) monitoring period is needed to be able to determine long-term net land subsidence (or uplift). Also, a longer record and experiments are needed to develop the most optimal subsidence monitoring system in peatlands.

References

- De Mulder, E.F.J., Geluk, M.C., Ritsema, I., et al. (in Dutch): De Ondergrond van Nederland. Geologie van Nederland, deel 7. Nederlands Instituut voor Toegepaste Geowetenschappen TNO, Utrecht. 379 p, 2003.
- Erkens, G., van der Meulen, M. J., Middelkoop, H.: Double trouble: subsidence and CO2 respiration due to 1,000 years of Dutch coastal peatlands cultivation, Hydrogeol. J., 24 (3), 551-568, 2016.
- Pleijter, M., van den Akker, J. J. H. (in Dutch): Onderwaterdrains in het veenweidegebied: toelichting op de methode en meetinrichting. Wageningen Environmental Research report nr 1586, 2007.
- Poland, J.F.: Guidebook to Studies of Land Subsidence Due to Ground-water Withdrawal. UNESCO report, ISBN 92-3-102213-X, 1984.
- Sneed, M., Brandt, J. T.: Land subsidence in the San Joaquin Valley, California, USA, 2007–2014, Proc. IAHS, 372, 23-27, 2015.
- Van Asselen, S., Erkens, G., Stouthamer, E., et al.: The relative contribution of peat compaction and oxidation to subsidence in built-up areas in the Rhine-Meuse delta, the Netherlands. Sc. Total Environ. 636: 177–191, 2018. ●